Sheltering 10 billion people in a warming and resource-scarce world: challenges and opportunities

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Chapter 2: Increasing material efficiencies of buildings to address the global sand crisis

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Abstract

There is a rapidly unfolding sand supply crisis in meeting growing material needs for infrastructure. We find a ~45% increase in global building sand use from 2020 to 2060 under a middle-of-the-road baseline scenario, with a 300% increase across low-and-lower-middle-income regions and a slight decrease in higher-income regions. Half of this growth may be avoidable using several material efficiency strategies in concert. International cooperation is essential for addressing vulnerabilities and inequalities.

2.1 Introduction

Buildings provide the basic human needs for shelter, social infrastructure and form the foundations of societies. The construction of buildings is also highly material-intensive and consumes a large amount of metallic (e.g., steel and copper) and non-metallic minerals (mainly concrete, brick, and glass)[1]. Previous studies have investigated the environmental impacts of building material production, along with potential mitigation strategies[2-4]. The scarcity of these materials has also seen recent attention[5] and prominent commentaries[6-8] have pointed to a severe global sand crises impacting regions as diverse as Cambodia, California, the Middle East, and China. Sand overexploitation has commonly driven ecosystem destruction/collapse (e.g., shoreline erosion, biodiversity and food loss, disaster resilience degradation) and is set to intensify as building demands increase.

The use of sand and gravel has seen the fastest increase in use across all solid materials used by humans and now represent the largest share of material use (around 68%-85% by mass), surpassing fossil fuels and biomass[9]. Sand is used mostly for making concrete or glass (with concrete comprising 98% of this use in the building sector) and requires chloride-free supplies (to prevent corrosion of other building materials) along with specific physical properties in terms of both size and shape. For example, desert sand is too smooth to be used as a binding agent for concrete and sea sand is too high in chloride levels for most construction purposes[10]. Most construction sand is extracted from rivers, lakes, and shorelines. Sand in these areas has long been a common pool resource, open to everyone largely because monitoring and restricting access to sand is difficult and costly[6]. In a rapidly growing market this has led to overexploitation and degradation. Even when regulated, illegal sand mining and trade has been reported in ~70 countries, often involving highly organized gangs or 'mafias' operating with the complicity of regulators[11]. The livelihoods of an estimated 3 billion people living along rivers are significantly threatened by long-term, unsustainable sand exploitation, along with deep impacts on ecology and land availability[7].

The coming decades are expected to see rapid growth in global building stock driven by population increases, urbanization, and economic development leading to higher living space requirements per inhabitant. However, for the sake of environment conservation, natural sand mining is likely to see increasingly strict regulation or even be banned in many areas[12]. To meet the growing material demand for buildings construction and avoid environmental deterioration due to excessive sand mining, the UN Environment Program has called for action to reduce building sand use through material efficiency strategies[12]. These aim to avoid over-building and over-design (overusing sand-based materials such as concrete), increase recycled materials, and increase the provision of alternative materials to natural sand[12]. However, we have a limited understanding of how sand demand evolves with building stock dynamics across the globe and where the reduction potentials of important material efficiency interventions may lie.

We develop a global dynamic model to investigate the amount of sand used in concrete and glass in residential and commercial buildings (representing nearly half of global concrete-related sand, see Supplementary Information Section 4.1) across 26 world regions by 2060. Sand used in non-building constructions (e.g., roads) and non-concrete/glass materials (e.g., mortar) are not considered. We evaluate this sand demand in a middle-of-the-road scenario that expects moderate population growth, economic and technological development and contains no new policies towards sustainable development[13] (consistent with the second Shared Socio-economic Pathway, or SSP2, see Methods).

2.2 Results

We show that, in this baseline scenario, annual global building sand demand sees a continuous increase from 3.2 Gt/yr in 2020 to 4.5 Gt/yr in 2060, seeing about 45% growth (see Supplementary Information Section 4 for a comparison between overall sand use in this study against the literature). Over half of the cumulative sand demand is seen in upper-middle-income regions, led by the China region, Middle East and Southeastern Asia (Figure 2.1a). However, these upper-middle-income regions see a decline in terms of both absolute and relative sense, from 1.9 Gt/yr (60%) in 2020 to 1.8 Gt/yr (40%) by 2060, mainly due to an overall population decline and stock saturation. High-income regions see similar declines. These trends are set against the rapid growth of the lower-middle-income regions, where annual demand more than triples from 0.7 Gt/yr (22%) to 2.2 Gt/yr (48%). The largest increase is seen in Western and Eastern Africa, where over 500% of current building sand demand is expected by 2060, followed by Rest of Southern Africa (419%), India (294%), and Rest of South Asia (269%) (Figure 2.1b).

We explore how building sand use might be reduced by implementing six widely suggested strategies, including a relative reduction in floor area by (i) more intensive use and (ii) building lifetime extension, (iii) reductions in concrete content by lightweight design, (iv) timber framing, and (v) component reuse, and (vi) natural sand substitution by alternatives (Supplementary Table S4). We also explore how the adoption of all six strategies simultaneously impact sand use. We assess both partial adoption (50% of total potentials) and complete adoption (100% of total potentials). See Methods and Supplementary Information Section 3 for full details.

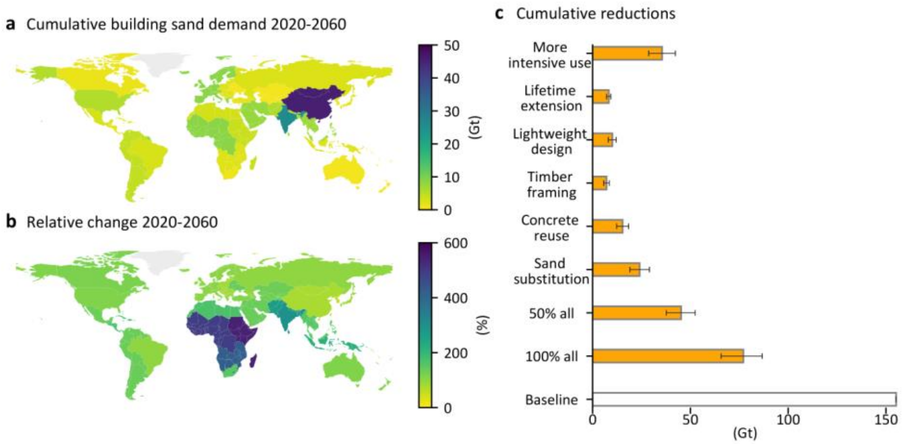

Figure 2.1 Building sand use and reduction scenarios in world regions. a, Cumulative building sand use during 2020–2060 under the baseline scenario. b, Baseline building sand use in 2060 relative to 2020. c, Cumulative sand reductions from material efficiency interventions. The whiskers represent the sensitivity intervals given by 20 percentage point variations for each strategy.

We find that cumulative building sand over 2020-2060 can be reduced by 5 to 23% from adopting each of these strategies individually and by 50% if all strategies are fully implemented simultaneously (Figure 2.1c). Among these strategies, more intensive use represents the largest cumulative sand reduction potential on a global level (~36 Gt) by avoiding surplus construction, growing urban regions in a compact way, reactivating vacant buildings, and more. Through lifetime extension, ~8 Gt natural sand can be avoided due to less frequent demolition and therefore less new construction. For a given building construction demand, a significant amount of sand could be reduced by lightweight design (~10 Gt), timber building substitution (~7 Gt), and concrete reuse (~15 Gt). Replacing natural sand with substitutes for concrete and glass production represents a major reduction potential (~24 Gt).

Priority areas for reducing building sand demand in one region may be less important in another. For example, more intensive use is very important in Europe, the USA, and China due to already spacious buildings (usually more than 40 m^2/cap for housing)[14] and commonly high vacancy rate. However, there is a limited potential for more intensive use in most African countries where people generally have inadequate building access (often below 20 or even 10 m^2/cap for housing)[14]. Policies to improve building longevity are especially important in regions like China and Japan, where the average lifespan is currently below 40 years, around half that found across European countries[14]. Similarly, the selection of alternatives to natural sand should be dependent on the local resource availability. For example, the use of crushed rock may only be a possibility in areas already close to suitable quarries (because of the high cost of transport).

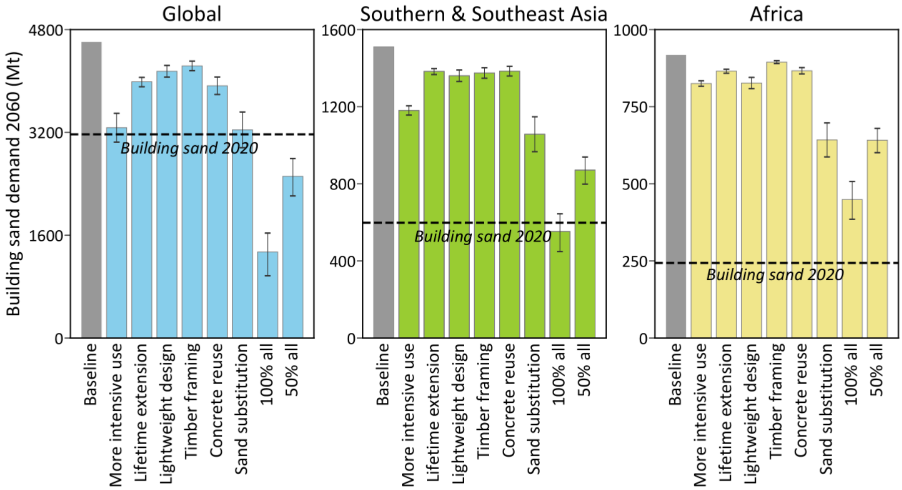

Figure 2.2 Building sand use in 2060 under the baseline and mitigation scenarios. The dashed horizontal lines represent building sand use in 2020. The whiskers represent the sensitivity intervals given by 20 percentage point variations for each strategy.

Since sand is formed by erosive processes over thousands of years, natural sand is currently being extracted at a rate far greater than its renewal[12]. Given the lack of reliable data on sand reserves, it is questionable if the current supply can be maintained or increased in the future, and therefore hard to evaluate if significant increases in sand demand can be met[15] (please see Supplementary Information Section 5 for more details on model limitations). The vulnerability of the building sector to sand supply, if defined as the ratio between future building sand demand and demand in 2020, is extremely unequal across world regions (Figure 2.1b, Figure 2.2). On a global level, either more intensive use or sand substitution could reduce the building sand demand in 2060 to lower than that in 2020. This means maintaining the current sand supply is likely enough for building construction using either of these two strategies. A global implementation of strategies at their 50% potential could reduce 2060 sand demand by 45% (or 71% with 100% implementation), which is approximately 79% of the demand in 2020 (or 42% with 100% implementation). However, if the current supply stays the same none of the six individual strategies alone nor a 50% adoption of all could reduce demand sufficiently by 2060 for some rapidly developing regions, such as Africa and Southern and Southeast Asia. In Africa, a full adoption of all strategies and a nearly-doubled natural sand supply from 2020 levels could be required to meet building construction demand by 2060.

International cooperation is likely essential in addressing the disproportionately distributed vulnerabilities of building sand demand, especially with respect to trade agreements. For example, Singapore has resorted to importing a total of 517 Mt of sand to meet a 20% land area expansion over the last 20 years[12]. However, this has led to soaring prices, environmental harm, and export bans across neighboring countries such as Cambodia and Indonesia[8,12]. Decentralization of exporting regions or even importing from remote regions (e.g., Dubai and Saudi Arabia have previously imported from Australia[12], and Greenland is suggested to be a promising sand exporter[16]) might be a solution to sand scarcity across neighboring countries. However, transport costs could be a challenge for long-distance shipping and the environmental and economic impacts of increased transportation remain highly uncertain. Trade agreements may be necessary in addressing these issues and avoiding or remediating environmental harm. Second, for sand-scarce countries it may be possible to import pre-processed or pre-fabricated building material elements (e.g., windows or pre-fabricated concrete parts) that represent virtual sand (i.e., sand embodied in products[10]), thus relieving pressures on domestic sand resources. Moreover, international cooperation in developing sustainable mining technologies and equipment (e.g., stone crushers) is critical for a sustainable sand industry transition in lower-income countries.

Sand substitutes (manufactured sand, desalted sea-sand and more) could play an increasingly important role, but there are challenges involved in the full life cycle from extraction to utilization. First, it is important to inventory locally available alternative resources and regulate the mining permissions. Quality control is a major task for the processing of manufactured sand and other alternatives for construction use. Standardized methods are needed to both control the fine content and impurities of these alternatives and also the addition of mineral and chemical admixtures to concrete to enhance the mechanical properties[17]. For in-use buildings using alternative sands, targeted quality inspections are needed to ensure no loss of function over time, especially when faced with environmental or climatic changes (e.g., increased subsidence or changes in temperature and humidity). Finally, while lab-scale lifecycle assessments generally show environmental benefits[17] from using sand substitutes in concrete, more research is needed for comprehensively monitoring and quantifying long-term environmental and social impacts of mining activities for sand alternatives (e.g., rock-derived mining and quarrying, and marine sand exploitation) to avoid problem shifting to other materials and negative tradeoffs.

A prominent barrier for a sustainable supply chain transition is the fragmentation of the sand and aggregate industry with 95% of global production represented by small and medium-sized enterprises (SMEs)[8]. The domination of SMEs brings several challenges not only in effective governance and accurate data collection, but for technological and equipment innovation since purchasing advanced fixed processing or manufacturing assets can be costly. Industry cooperatives or consolidation may be advantageous for applying stricter mining permissions and restrictions[8], but such developments come with its own dangers of regulatory capture and political influence[18].

In general, the implementation of material efficiency strategies investigated here would also yield significant greenhouse gas (GHG) emissions reduction[2,4], and therefore are also being driven by climate targets on a global level. Collaborative efforts to conserve sand and mitigate emissions provide large opportunities, from reducing local mining pressures to lowering overall GHG emissions, in a more efficient and sustainable building sector. This analysis develops a picture of global building sand dynamics, highlights major opportunities and challenges of building sand reduction across global regions. We hope this stimulates progress in this crucially important yet underreported area.

2.3 Methods

We developed an integrated global dynamic building-sand model (GloBus) for the assessment of sand use for building material production. We use this to investigate the sand use reduction from different material efficiency interventions (see the model framework in Supplementary Figure 1). We include 4 residential buildings types (detached houses, semi-detached houses, apartments, and high-rise buildings) in urban and rural areas, and 4 non-residential buildings types (offices, retails & warehouses, hotels & restaurants, and other commercial buildings). We evaluate sand used for concrete and glass in buildings by 2060. This period is particularly appropriate as projections suggest it will be within the period of a global population peak and a rise of living standards across lower-income regions which would significantly shape the global building stock profiles (in the absence of extreme climate disruption)[2,4]. A brief description of the model components is given here with full details provided in the Supplementary Information.

Building concrete and glass use

We develop a stock-driven dynamic model to calculate the concrete and glass use for building construction on the basis of refs[4,13,14,19]. Specifically, we first translate the regional socioeconomic trends (i.e., population, GDP, housing space per person, and building type split) into the demand of residential and commercial building stocks on a yearly basis. We then calculate the annual construction (inflow) and demolition (outflow) of building floor space based on documented lifetime distributions. To do this, we first calculate the demolition from the existing building stock using the lifetime model. Then, the construction can be calculated using the basic mass balance (inflow = outflow +stock change). We next estimate the concrete and glass inflows for building construction by combining floor space inflow with the material intensity (in kg/3), which in turn define the demand for sand based as detailed below. For full details please see the Supplementary Information.

Building sand use

Due to a lack of reliable data on sand use, previous estimates are mainly indirect, i.e., based on the sand requirement as a ratio of other material requirements such as cement and bitumen[10,12]. Here we estimate the sand use as a ratio for each metric ton of concrete and glass using weight ratios derived from a number of lifecycle inventory databases and studies (see the Supplementary Information for details).

Scenario development

We first explore a baseline scenario to represent the middle-of-the-road path in that is consistent with the shared socioeconomic pathway SSP2. Data in the baseline scenario are mainly derived from the integrated assessment model IMAGE[13] and complementary studies[14,20]. We then explore eight scenarios whereby the first six give results when the interventions are implemented independently, and the final two when all six strategies are adopted simultaneously at 50% (halfway towards total maximum potential modelled here) and 100% (total maximum potential). Details of all scenarios and interventions are available in Supplementary Information Section 3. Note that this study aims to explore potentials rather than predict the future. Given the data constraints, the model is subject to several limitations as discussed in Supplementary Information Section 5.

2.4 Data availability

This research relies entirely on publicly available data as referenced. We have also deposited them in the Zenodo repository[21] in a form that can be easily used with our model code. Source data are provided with the paper (https://www.nature.com/articles/s41893-022-00857-0#Sec8).

2.5 Code availability

The python code of the building sand model is publicly available from the Zenodo repository[21].

2.6 Supplementary information

See details: https://static-content.springer.com/esm/art%3A10.1038%2Fs41893-022-00857-0/MediaObjects/41893_2022_857_MOESM1_ESM.pdf.

2.7 References

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